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Quantifying Geoacoustic Uncertainty and Seabed Variability for Propagation Uncertainty

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LONG-TERM GOALS

Propagation and reverberation of acoustic fields in shallow waters depend strongly on the spatial variability of seabed geoacoustic parameters, and lack of knowledge of seabed variability is often a limiting factor in acoustic modeling applications. However, direct sampling (e.g., coring) of vertical and lateral variability is expensive and laborious, and matched-field and other long-range inversion methods fail to provide sufficient resolution. The long-term goal of this work is to use a Bayesian inversion approach in combination with seabed reflectivity data to investigate and quantify spatial variability of seabed sediments in two and three dimensions. For proper quantitative examination of spatial variability, it is important to differentiate between parameter estimate uncertainty, model parameterization effects, and actual spatial variability.

This project is based on work that was developed during Dettmer's PhD and postdoctoral research. To date, the project has developed an approach to quantify spatial variability of seabed sediments along a track (Dettmer et al. (2009a), Dettmer et al. (2009b)). Inversion results for multiple locations are analyzed and the one-dimensional (1D) uncertainty results between sites are compared to understand sediment variability. In particular, rigorous methods for selecting the optimal model parameterizations (e.g., the number of sediment layers) were examined and applied. Further development of this methodology is an ongoing effort that will lead to rigorous two-dimensional (2D) and three-dimensional (3D) geoacoustic uncertainty estimates.

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14. ABSTRACT
Propagation and reverberation of acoustic fields in shallow waters depend strongly on the spatial variability of seabed geoacoustic parameters, and lack of knowledge of seabed variability is often a limitingfactorin acoustic modeling applications.However, direct sampling (e.g., coring)ofverticaland lateral variability is expensive and laborious, and matched-field and other long-range inversion methods fail to provide sufficient resolution. The long-term goal of this work is to use a Bayesian inversion approach in combination with seabed reflectivity data to investigate and quantify spatial variability of seabed sedimentsintwoand three dimensions.For proper quantitativeexaminationof spatial variability, it is important to differentiate between parameter estimate uncertainty, model parameterization effects, and actual spatial variability.

15. SUBJECT TERMS

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OBJECTIVES

The objective of this research is to develop a new methodology to quantify 2D geoacoustic parameters and uncertainties to permit prediction of sonar performance uncertainties, as a step towards full 3D uncertainty estimation and verification. One-dimensional inversion results of wide-angle reflection data will be extended to 2D by interpolating geoacoustic parameters and uncertainties between reflection sites, guided by connecting data, when available (e.g., high-resolution seismic, towed-array acoustic data, AUV data), and prior information from geologic interpretations. Results will be verified by comparing transmission loss (TL) uncertainty predictions with measured TL. The methodology will be developed using a variety of existing data.

APPROACH

The approach is to extend 1D inversion results to 2D by interpolating geoacoustic parameters and uncertainties between wide-angle reflection coefficient sites. Bayesian inference is used to determine model parameters of 1D sediment profiles and their uncertainties from seismo-acoustic single bounce reflectivity measurements with small seafloor footprints ($\sim$100 m) (Dettmer et al. 2007ab 2008 2009ab). Guided by connecting data (e.g., high-resolution seismic and/or towed-array acoustic data) and prior information from geologic interpretations, these 1D results can then be used to build a 2D sediment model including uncertainty estimates. In this case, rigorous uncertainty estimation for the individual 1D inversions is essential to determine whether observed differences are due to actual environmental variability or simply result from uncertain parameter estimates.

Results will be verified by comparing TL uncertainty predictions with measured TL data. The methodology will be developed using existing data. Data collection was planned/attempted off the northeast coast of Taiwan under the QPE Uncertainty DRI , but challenging weather conditions precluded useful measurements (see following section). However, it is anticipated that this project will lead to significant practical and theoretical advances in understanding and quantifying uncertainty/variability that will be applicable to QPE.

Bayesian inversion formulates an inverse problem in terms of the posterior probability density (PPD) of the model parameters, incorporating both data and prior information. The solution is typically quantified in terms of properties of the multi-dimensional PPD representing parameter estimates, uncertainties and inter-relationships. Optimal parameter estimates require nonlinear optimization such as adaptive hybrid inversion (Dosso 2002). Parameter uncertainties (e.g., marginal distributions, credibility intervals) are computed using Markov-chain Monte Carlo methods (Dosso 2002; Holland et al. 2005; Dettmer et al. 2007ab 2008 2009ab).

Rigorous uncertainty estimation for geoacoustic parameters is of key importance to meaningfully resolve spatial variability between inversion results for nearby measurement sites from the inherent inversion uncertainties. This requires a nonlinear inversion approach, rigorous estimation of the data error statistics, and quantitative model selection (i.e., parametrization).

Uncertainty estimates depend strongly on the model parametrization chosen for the inversion. Bayesian evidence is the basis for this model selection. Evidence brings a natural parsimony to the model selection problem which is referred to as the Bayesian razor. Estimating evidence is challenging due to the requirement to integrate the likelihood with respect to the prior (Chib 1995), and finding robust and accurate estimators for the evidence integral has seen the attention of much research. Due to the high computational demands of the forward and inverse problems considered in this paper, an asymptotic point estimate (for the MAP model vector) is used to carry out model selection. The Bayesian information criterion (BIC, Schwartz (1978)) is an asymptotic approximation derived for diffuse multivariate normal prior distributions (Kass and Raftery 1995).

WORK COMPLETED

In the first year of this project, work was focused on planning two efforts to collect geoacoustic data in the East China Sea as part of the QPE Uncertainty DRI. In addition, algorithm development and analysis of existing data were carried out to complete two peer reviewed publications on geoacoustic uncertainty/variability in the Journal of the Acoustical Society of America (Dettmer et al. 2009ab). These results are summarized in the following section; the data collection attempts are described below.

The first cruise was planned for June 8–12, 2009, with the Taiwanese RV Ocean Researcher 2. Cruise planning was difficult since ship time and technical support could only be secured at a late date. Our Taiwanese colleagues, Prof. Chi-Fang Chen and Dr. Linus Chiu, made a tremendous effort to obtain the ship time and highly qualified technicians.

Since weather and sea conditions are often poor in the western Pacific, we planned to bring along two acoustic sources for the wide angle reflection coefficient measurements. A boomer source was rented since it has been successfully used for this experiment several times. In addition, an Edgetech SB512i Chirp source was provided by the Taiwanese for use in sea surface conditions that would not allow the boomer to be deployed. To raise confidence in the Chirp source for reflection coefficient measurements, extensive modeling was carried out to determine the type of chirp as well as optimal tow depth. As a receiver, a one-channel Woods Hole SHRU was used. Dettmer traveled to Woods Hole to familiarize himself with the receiver and its operation in April, 2009.

The experiment was challenged by rough sea surface conditions from the first day of the cruise. The SHRU was deployed on the first night but only the Chirp source could be deployed. The Chirp source was towed but the main cable was soon damaged due to strong currents and could not be repaired at sea. The next morning, a SHRU from National Sun Yat-Sen University was deployed and the boomer source was towed. However, with deteriorating weather, the sea state was getting much too high for the boomer source and operations had to be abandoned. The quality of the collected data was very poor since the boomer catamaran was rocking in the waves to a degree where the directional signals could not be used for meaningful analysis. After recovering all gear and two other moorings for our Taiwanese colleagues, the ship had to return to port and could not go out again due to poor weather.

A second cruise was organized due to the disappointing outcome of the first cruise and took place from September 3–7, 2009. This time, three different sources were planned to be used to account for the difficult sea conditions. The SB512i Chirp was supposed to provide sub-bottom profiler data along tracks, as well as wide angle reflection coefficient measurements. Further a SQ23 and a J-9 source were taken to provide robust point sources that could be towed at depth in difficult conditions. For these sources, modeling was carried out to determine optimal tow depths and pulse/chirp shapes. Unfortunately, similarly poor conditions prevailed during this time period. The OR2 made several attempts to reach the QPE target box. The target box was finally reached, but the ship captain insisted on returning to port the first night at sea due to safety concerns.

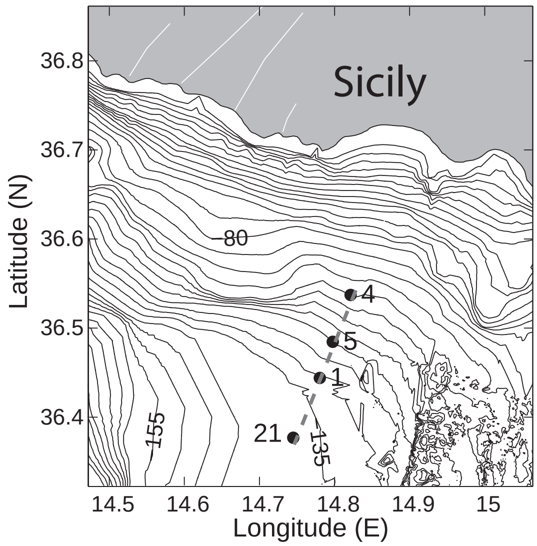

Figure 1: Bathymetry of the Malta Plateau with the locations of sites 4, 5, 1, and 21. The dashed line indicates the chirp bottom-profiler track of ~ 20 km length.

RESULTS

The results presented in this section focus on some of the research carried out this year to quantify geoacoustic variability. A more complete account is presented in Dettmer et al. (2009b). Quantifying spatial variability is a key step towards understanding 2D geoacoustic uncertainty models, and requires a rigorous methodology to differentiate between uncertainty estimates and inherent variability. To meaningfully analyze variability between measurement sites requires addressing several important issues: (i) determining a geoacoustic parameterization for each site that represent only structure supported by the data (carried out here using Bayesian model selection), (ii) rigorous geoacoustic uncertainty estimation for each site so that lateral variability can be differentiated from inherent inversion uncertainties (nonlinear Bayesian inference), and (iii) a quantitative measure of parameter differences that accounts for uncertainties (e.g., the Bhattacharyya coefficient).

Reflection inversions were carried out for four sites along a track on the Malta Plateau (Fig. 1) using Bayesian inference. Model selection based on the BIC was applied to determine appropriate parameterizations in terms of the number of sediment layers comprising the seabed model. The sediment sound-velocity and density profiles computed via reflection inversion agreed well with core measurements at each site.

The inversion results for the four sites are used to infer information about the spatial variability of the seabed along the track. Figure 2 shows the inversion results for one of the sites, site 21, as well as a shallow core measurements taken at the site.

Pairs of adjacent sites are compared qualitatively and examined for common features. Four main features are identified in the inversion results (Fig. 3). First, a low-velocity sediment layer is present at all sites and decreases in thickness from north to south. Below this sediment wedge, a high-velocity layer appears at site 5 (approximately 13 km along the track) and is also present at site 1. Below the high-velocity layer, a change in basement sound velocity between sites 5 and 1 indicates a potential

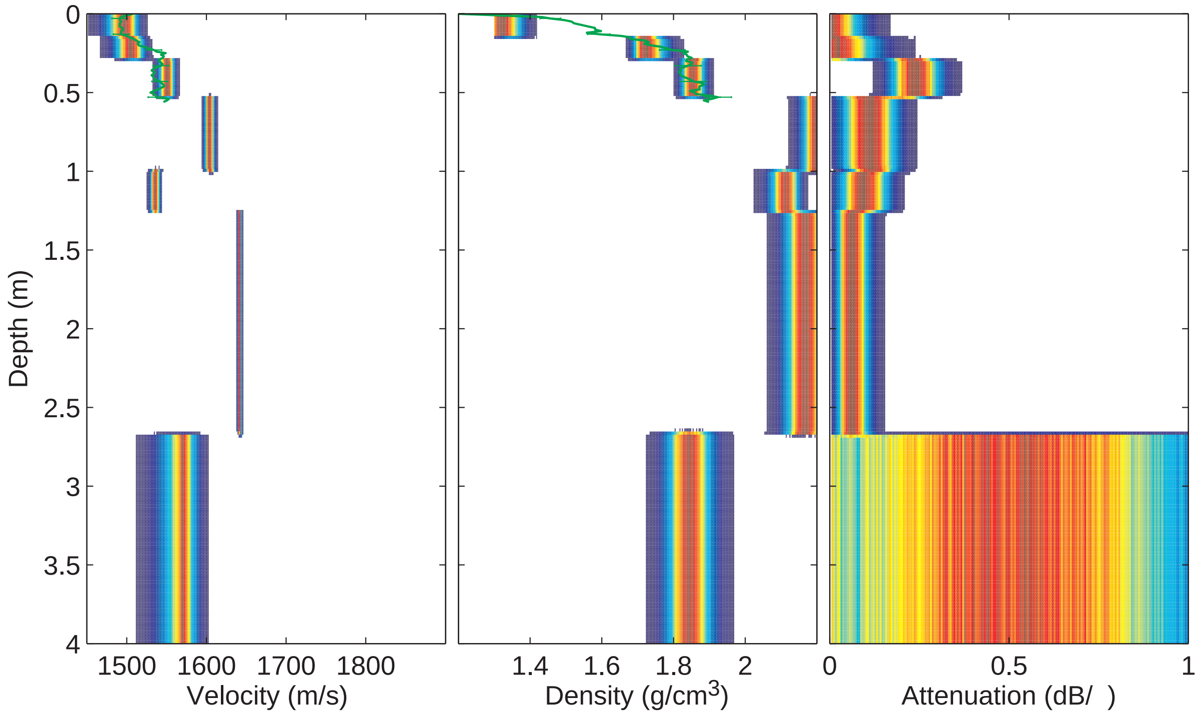

Figure 2: Marginal-probability depth distributions for site 21. Core measurements indicated by green line with error bars on every fifth point for sound velocity and density

additional layer that pinches out between these two sites. Finally, a prominent high-velocity layer present only at site 21 indicates an additional layer pinching out between sites 1 and 21.

The continuity of these main features are examined quantitatively by measuring the overlap of sound-velocity profile marginal probability distributions with the Bhattacharyya coefficient (BC, Fig. 4). The BC clearly quantifies the presence of the low-velocity wedge as well as the change in the sediment half-space between sites 5 and 1. The BC also indicates significant overlap of the half-space sediment properties between sites 1 and 21.

The inversion results are compared to the geologic interpretation of a chirp sub-bottom profile (Fig. 3) which identifies the low-velocity sediment wedge, the high-velocity layer, a layer that pinches out between sites 1 and 21, and a change in lower half-space velocity between sites 5 and 1. The chirp section clearly matches the main layers in the inversion results.

The results presented in this section indicate that inversion of reflection-coefficient data can provide high-resolution geoacoustic profiles with uncertainties suitable for interpretation of lateral variability between measurement sites.

IMPACT/APPLICATIONS

The ability to obtain remotely (i.e., without direct sampling) seabed parameters has important implications for science (e.g., providing data for understanding sediment processes), the Navy (e.g., improving databases for ASW and MCM), as well as many commercial applications (e.,g., pipeline or

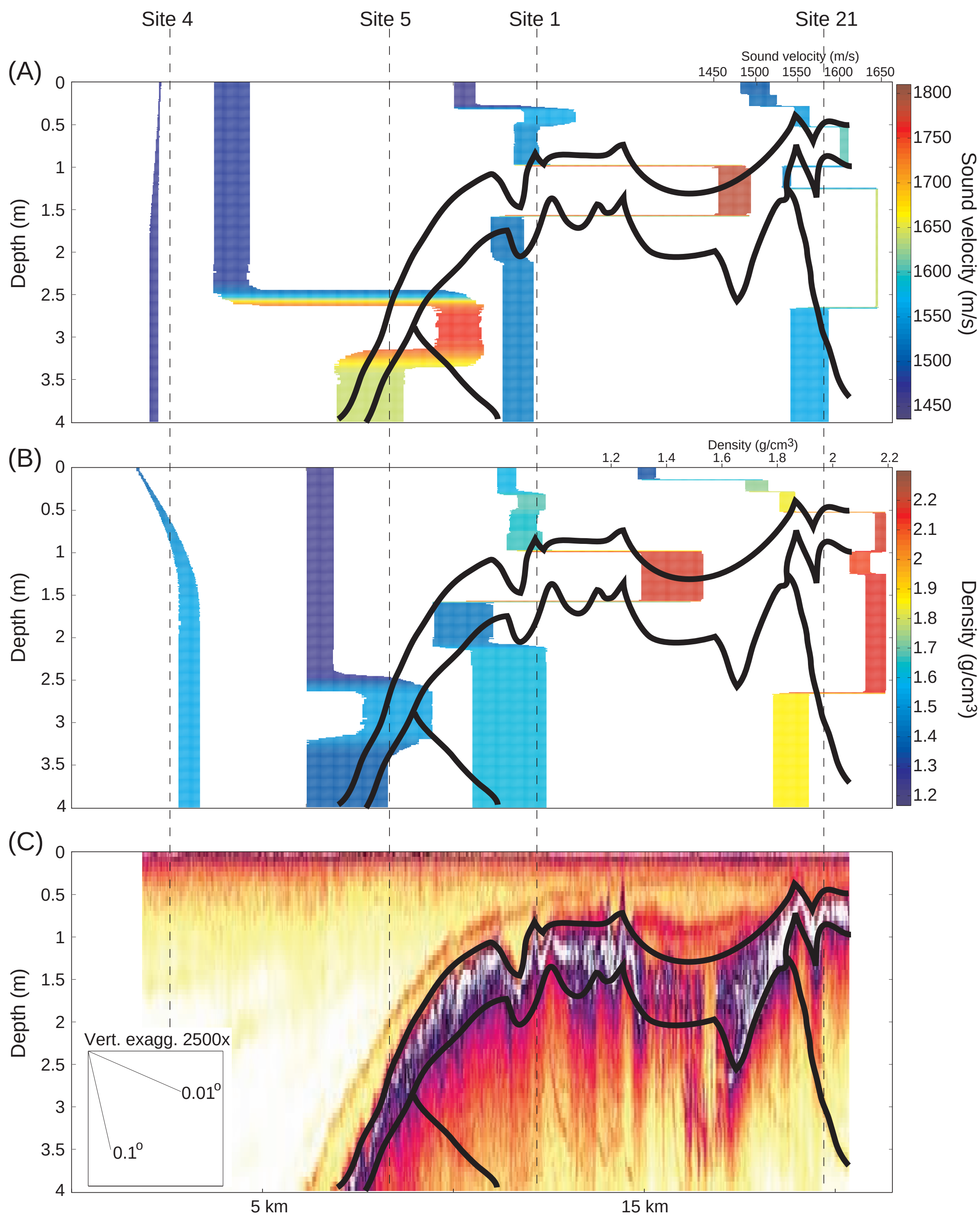

Figure 3: Mean sound velocity (A) and density (B) profiles compared for all sites. Widths of shaded areas correspond to 90% highest-probability density credibility intervals. Panel (C) shows the chirp bottom-profiler section with the solid lines indicating a basic geologic interpretation.

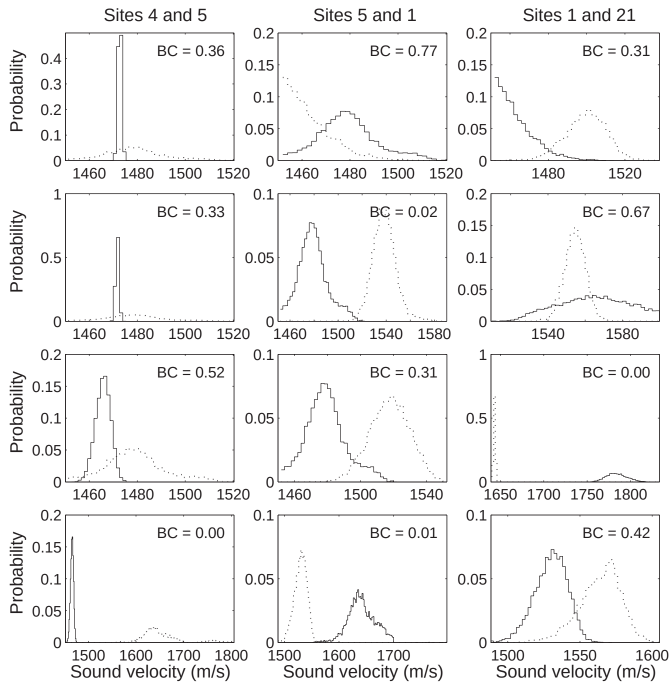

Figure 4: Marginal probability distributions for selected depths for each pair of adjacent sites. Solid lines indicate the northern site of the pair, dotted lines the southern site.

cable laying). A particular strength of the present work is quantifying the uncertainties of the seabed parameters. Two-dimensional geoacoustic uncertainty models will impact the reliability and quality of transmission loss prediction.

RELATED PROJECTS

Broadband Clutter JRP project (NURC, ARL-PSU, DRDC-A, NRL)
ONR QPE Uncertainty Program

REFERENCES

J. Dettmer, S. E. Dosso, and C. W. Holland. Model selection and Bayesian inference for high resolution seabed reflection inversion. *J. Acoust. Soc. Am.*, 125:706–716, 2009a.

J. Dettmer, C. W. Holland, and S. E. Dosso. Analyzing lateral seabed variability with Bayesian inference of seabed reflection inversions. *J. Acoust. Soc. Am.*, 126:56–69, 2009b.

J. Dettmer, S. E. Dosso, and C. W. Holland. Uncertainty estimation in seismo-acoustic reflection travel-time inversion. *J. Acoust. Soc. Am.*, 122:161–176, 2007a.

J. Dettmer, S. E. Dosso, and C. W. Holland. Full wave-field reflection coefficient inversion. *J. Acoust. Soc. Am.*, 122:3327–3337, 2007b.

J. Dettmer, S. E. Dosso, and C. W. Holland. Joint time/frequency-domain inversion of reflection data for seabed geoacoustic profiles. *J. Acoust. Soc. Am.*, 123:1306–1317, 2008.

S. E. Dosso. Quantifying uncertainty in geoacoustic inversion. I. A fast Gibbs sampler approach. *J. Acoust. Soc. Am.*, 111:129–142, 2002.

C. W. Holland, J. Dettmer, and S. E. Dosso. Remote sensing of sediment density and velocity gradients in the transition layer. *J. Acoust. Soc. Am.*, 118:163–177, 2005.

S. Chib. Marginal likelihood from the Gibbs output. *J. Am. Stat. Assoc.*, 90:1313–1321, 1995.

G. Schwartz. Estimating the dimension of a model. *Ann. Statist.*, 6:461–464, 1978.

R. E. Kass and A. E. Raftery. A reference Bayesian tets for nested hypotheses and its relationship to the schwarz criterion. *J. Am. Stat. Assoc.*, 90:928–934, 1995.

PUBLICATIONS

J. Dettmer, C. W. Holland, and S. E. Dosso. Analyzing lateral seabed variability with Bayesian inference of seabed reflection data. *J. Acoust. Soc. Am.*, 126:56–69, 2009 [published, refereed].

J. Dettmer, S. E. Dosso, and C. W. Holland. Model selection and Bayesian inference for high resolution seabed reflection inversion. *J. Acoust. Soc. Am.*, 125:706–716, 2009 [published, refereed].